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RESEARCH MEMORANDUM

INCREASE IN STABLE-AIR-FLOW OPERATING RANGE OF A MIXED-FLOW COMPRESSOR BY MEANS OF A SURGE INHIBITOR

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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INCREASE IN STABLE-AIR-FLOW OPERATING RANGE OF A MIXED-FLOW COMPRESSOR BY MEANS OF A SURGE INHIBITOR

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SUMMARY

The problem of increasing the stable-air-flow operating range of a mixed-flow compressor operating at high impeller tip speeds by recirculating a minimum amount of the compressor-discharge air and utilizing part of the energy of compression to produce pre-rotation at the impeller inlet has been investigated. A description and the design principles of a surge inhibitor used for this research are presented.

The results of tests of the compressor unit with the surge inhibitor installed showed that a considerable gain in stable-air-flow operating range was obtained over the range of equivalent impeller tip speeds from 1255 to 1738 feet per second. The surge inhibitor, although designed to triple the stable-air-flow operating range at an equivalent impeller tip speed of 1550 feet per second, was capable of increasing the net stable-air-flow operating range more than eight times its original value at this tip speed.

When the surge inhibitor was inoperative, the efficiency and the pressure ratio in the normal stable-air-flow operating range was not impaired. At equivalent impeller tip speeds of 1653 and 1738 feet per second, the surge inhibitor permitted operation through a critical flow condition into a stable region of higher efficiency and pressure ratio. An increase of 5 points in efficiency and a corresponding increase of 0.63 in pressure ratio were obtained at these tip speeds. Except where the surge inhibitor was used to pass through the critical flow condition at high impeller tip speeds, recirculation of air caused a decrease in both pressure ratio and efficiency.

INTRODUCTION

The operating range over which a compressor of the type used for aircraft power plants can deliver a stable air flow is limited for maximum air flow by the occurrence of sonic velocities somewhere in the flow path and for minimum air flow by the surge point. Unstable air flow, or surging, is accompanied by a sharp loss in aerodynamic compressor performance and may cause serious mechanical vibration and unstable operation in an engine installation. As the impeller tip speed is increased to the high values necessary for high pressure ratios, the stable-air-flow operating range of the compressor is reduced until the points of maximum and minimum volume flow coincide. At these high tip speeds, the conditions of peak efficiency and peak pressure ratio are therefore usually very close to the surge point. Although operation of the compressor near the surge point is desirable for peak performance, this procedure becomes undesirable in practice because of the possibility of operation in the surge region.

The difficulties in obtaining efficient and stable operation at high impeller tip speeds and pressure ratios could be eliminated if it were possible to suppress the surge point and extend the stable-air-flow operating range to lower values of volume flow. Examples of research in suppressing the surge point and extending the stable-air-flow operating range are presented in references 1 and 2. The methods that have been proposed are: modifications to impeller and diffuser blading, resonant chambers, stationary and rotating air-prerotation devices at the impeller inlet, and recirculation of compressor-discharge air to the impeller inlet. Another proposed method, which circumvents operation at the surge point rather than suppresses the surge point, involves bypassing part of the compressor-discharge air around the receiver.

The problem of increasing the stable-air-flow operating range of a compressor at high impeller tip speeds by means of a device combining two of these methods has been investigated at the NACA Cleveland laboratory. A minimum amount of compressor-discharge air is recirculated in such a manner as to utilize part of the energy of compression to produce prerotation at the impeller inlet. This principle of surge suppression allows the compressor to operate with a quantity of volume flow within the stable-air-flow operating range, although the net volume flow delivered by the compressor would normally be in an unstable-air-flow operating range.

A surge inhibitor designed to produce the required recirculation and prerotation was tested in conjunction with a compressor consisting of a mixed-flow impeller and a semivaneless diffuser. Previous tests of this compressor (reference 3) had shown that the air-flow operating range at high impeller tip speeds was very limited and that the maximum pressure ratio at an equivalent impeller tip speed of 1565 feet per second was higher than that at 1644 feet per second and equal to that at 1740 feet per second. The effectiveness of this surge inhibitor in extending the stable-air-flow range of the compressor is presented in this report. A description of the surge inhibitor and the design principles are also given.

SURGE INHIBITOR

Description. - The essential elements of the surge inhibitor are a scroll inlet and an air-acceleration passage formed by two parallel walls. The surge inhibitor consists of two symmetrical sections. Photographs of the surge inhibitor at various stages of assembly are shown in figure 1. The rear section of the surge inhibitor was mounted on the test rig by studs near the inner diameter; the studs were flush with the walls of the acceleration passage. Four through bolts provided additional mechanical strength and prevented misalinement of the surge inhibitor with the inlet-bearing support. The assembly of the two sections of the surge inhibitor is shown in figure 1(b) and the surge inhibitor with the inlet-bearing support is shown in figure 1(c).

The compressor-discharge air is received from a radial outlet on the collector case and directed to the scroll inlet. The scroll inlet imparts a tangential-velocity component to the air and uniformly distributes the air at the entrance of the acceleration passage. The recirculated air is then accelerated through the passage formed by the parallel walls and discharged into the impeller-inlet air stream with a large tangential-velocity component with respect to the radial-velocity component. The diameter at which the recirculated air enters the inlet-air stream is determined by the inside diameter of the impeller front shroud. The axial location of the recirculated-air discharge slot in front of the impeller-inlet blades is determined by the impeller front-shroud flange, as shown in figure 2.

Design principles. - The surge inhibitor has the two-fold function of introducing part of the compressor-discharge air into the air stream at the impeller inlet and of rotating this recirculated air in the direction of impeller rotation. At any point along the periphery of the recirculated-air discharge slot, the angle between the direction of flow of the recirculated air and the tangent to the point is approximately 20° (fig. 1(a)). By the introduction of the recirculated air into the impeller-inlet air stream with a large tangential-velocity component (800 ft/sec at the design condition), part of the energy of compression is utilized to prerotate the inlet air and thus relieve the impeller of part of the work required to obtain a given pressure ratio. Because the tips of the impeller inlet blades operate at a high Mach number and reach a condition of critical flow before the rest of the leading edge of the blades, the prerotation added by the recirculated air in this particular manner tends to delay the occurrence of compression shocks in this region, as well as to decrease the relative angle of attack of the inlet air on the leading edge of the impeller blades.

The design of the surge inhibitor was based on predetermined performance characteristics of the compressor unit (reference 3). The amount of air to be recirculated to the impeller inlet was established by the quantity necessary to triple the existing stable-air-flow operating range at the equivalent impeller tip speed of 1550 feet per second. The geometry of the surge inhibitor is determined by the quantity of compressor-discharge air necessary to be recirculated, the inlet- and compressor-discharge-air conditions, and the assumed angle of flow at the discharge of the surge inhibitor. When these quantities are given, the profiles of the passages are determined from the continuity, the energy, and the momentum equations. The scroll inlet was designed to have a uniform decrease in area along the periphery.

APPARATUS

Compressor unit. - The 23-blade impeller described in reference 3 is of the mixed-flow type in that it discharges the air with an axial-velocity component. The impeller has an annulus diameter of 11.00 inches, an inlet-hub diameter of 4.26 inches, and a maximum tip diameter of 14.74 inches.

The semivaneless diffuser, also described in reference 3, has an over-all diameter of 28.00 inches. The diffuser consists of a vaneless section followed by a 32-vaned section at a diameter of 20.67 inches.

The inlet-bearing support used in the tests of reference 3 required an alteration because of the surge-inhibitor installation (fig. 2). The insertion of the surge inhibitor necessitated moving the inlet-bearing support farther upstream of the impeller. This relocation placed the symmetrical airfoil-shaped struts of the inlet-bearing support approximately $1\frac{3}{4}$ inches farther upstream of the impeller than in the test installation described in reference 3. The struts are offset from a radial line and are nearly tangential with the inlet-bearing housing. The inlet-bearing housing was so extended that the bearing itself remained at its original position with respect to the impeller because of the fixed location of the outboard bearing for the impeller stub shaft.

Test rig. - The compressor unit with the surge inhibitor was tested in a variable-component test rig. A description of a variable-component test rig is given in reference 4. The complete test setup is shown in figure 3. A 3000-horsepower variable-frequency induction motor coupled to a speed increaser was used to drive the impeller.

Impeller-inlet air was metered through a calibrated adjustable submerged orifice and was passed through an inlet throttle to a large air-filter tank before entering the straight length of inlet pipe leading to the impeller. The air was discharged from the large variable-component collector case through two tangential discharge pipes into the atmospheric-exhaust system. When the surge inhibitor was put into operation, part of the discharge air passed from the variable-component collector case through a radial pipe, a submerged flat-plate orifice, a gate valve, and a butterfly throttling valve to the scroll inlet of the surge inhibitor. The gate valve, which was used solely to prevent air leakage when the surge inhibitor was not operating, was fully opened after initial surging was encountered.

The surge inhibitor, the variable-component collector case, and the inlet and discharge pipes were lagged to minimize heat-transfer effects between the test setup and the ambient air.

Instrumentation. - A standard NACA differential-pressure recorder (references 5 and 6) was connected to total- and static-pressure tubes in one of the discharge pipes to obtain a trace of the discharge velocity-pressure variation during the sequence of operations of stable air flow, surging, and recovery of stable air flow by means of the surge inhibitor.

The net volume flow through the compressor unit was measured with a calibrated adjustable submerged orifice. The recirculated-air weight flow was measured with an A.S.M.E. standard submerged orifice that was preceded by 14 diameters of straight pipe and followed by straight pipe for 5 diameters.

The pressure- and temperature-measuring station in the inlet pipe was located 2 diameters upstream of the impeller inlet and was preceded by 10 diameters of straight pipe. The discharge measuring station was preceded by straight pipe for a length of 12 diameters. The measuring station in the recirculation pipe was preceded by straight pipe for a length of 11 diameters from the collector case. Measurements were taken in accordance with the recommendations of references 7 and 8.

Pressure and temperature measurements were taken in pairs to eliminate erroneous readings. Air pressures were indicated by mercury manometers with the exception of pressure differentials for volume-flow measurements, which were indicated by water manometers. Temperatures were measured with calibrated iron-constantan thermocouples.

The speed of the impeller was measured with an electric chronometric tachometer; the impeller tip speed was based on the maximum diameter of the impeller.

The precision with which all measurements were made is estimated to be within the following limits:

Temperature, $^{\circ}F$	± 0.5
Pressure, inches of mercury	± 0.02
Net volume flow, percent	± 0.5
Recirculated-air weight flow, percent	± 1.25
Impeller tip speed, percent	± 0.5

TEST METHODS

Tests were made with ambient impeller-inlet air over a range of equivalent impeller tip speeds of 1255 to 1565 feet per second corrected to a standard NACA inlet-air temperature of 59° F. The inlet-air temperature varied from 72° to 87° F for the tests with ambient inlet air. Tests at equivalent impeller tip speeds of 1653 and 1738 feet per second were made with refrigerated inlet air at temperatures of -8° and -25° F, respectively. For all tests, the temperatures of the inlet air at any particular speed did not vary by more than $\pm 2^{\circ}$ F.

The tests were conducted in accordance with the recommendations of reference 7 whenever possible. All tests were made with open outlet throttle and the volume flow was varied by the inlet throttle. Upon initial surging of the unit, the gate valve in the recirculation pipe was fully opened and the butterfly throttling valve was set to allow the minimum amount of discharge air necessary to recirculate through the surge inhibitor to suppress surging. The inlet throttle was further closed until surging was again encountered and the butterfly throttling valve further opened until surging ceased. This sequence of operation was repeated from closed to fully open throttle in the recirculation pipe.

RESULTS AND DISCUSSION

Performance calculations were made in accordance with the method of reference 7. Recirculated-air weight-flow calculations were made as recommended by A.S.M.E. standards (reference 8). The data are presented in accordance with the recommendations of reference 9. Performance curves are also presented to show the increase in net stable-air-flow operating range and the efficiency obtained with the surge-inhibitor installation as compared with the tests of the compressor unit without the surge inhibitor (reference 3). Curves showing the percentage of net air weight flow necessary for recirculation to the impeller inlet for a given increase in net stable-air-flow operating range are also presented.

A typical velocity-pressure trace taken in one of the discharge pipes is shown in figure 4. The sequence of operations represented is: stable air flow, surging, and recovery of stable air flow by the surge inhibitor. Once surging had been suppressed, the quantity of recirculated air could be slightly reduced without the recurrence of surge.

Extension in Stable-Air-Flow Operating Range

A comparison of the stable-air-flow operating range of the compressor unit with and without the surge inhibitor installed is presented in figure 5. The performance characteristics of the compressor unit without the surge inhibitor were obtained from reference 3. The maximum volume flow for a given tip speed was found to be higher for this series of tests than for those of reference 3. This shift in the curves to higher values of volume flow was probably caused by the improved air-flow conditions at the impeller inlet resulting from relocation of the inlet-bearing support $1\frac{3}{4}$ inches farther upstream of the impeller. A more uniform velocity distribution at the impeller inlet was established by reducing the interference effect of the struts and by allowing more distance between the abrupt reduction in diameter at the inlet-bearing support and the impeller.

The extension of the net stable-air-flow operating range to lower net volume flows was entirely due to the operation of the surge inhibitor. The surge inhibitor, although designed to triple the stable-air-flow operating range at an equivalent tip speed of 1550 feet per second, was capable of increasing the net stable-air-flow operating range more than eight times its original value at this tip speed. A considerable gain in net stable-air-flow operating range was obtained at all impeller tip speeds, particularly at the equivalent tip speed of 1653 feet per second, where no flexibility in stable-air-flow operating range was previously obtained.

At the equivalent tip speed of 1653 feet per second, surging occurred at approximately the same pressure ratio, 3.12 (point A on fig. 5), as that for the compressor unit without the surge inhibitor. When the surge inhibitor was allowed to recirculate enough discharge air to suppress surging, it was possible to close the inlet throttle a small amount, to close off completely the recirculated air, and still to maintain stable air flow. When this aerodynamically critical point was passed, a decrease in net equivalent volume flow from 14,800 to 14,350 cubic feet per minute (point B on fig. 5) was obtained without the use of the surge inhibitor. For volume flows less than that at point B, recirculated air was again necessary; the net volume flow was 6900 cubic feet per minute when the maximum possible amount of air was recirculated.

At the equivalent tip speed of 1740 feet per second, the original compressor unit (without the surge inhibitor) pulsated mildly from a pressure ratio of approximately 3.00 to the point of violent surging. With the surge inhibitor installed but not in operation, these pulsations were eliminated. As previously stated, the improvement in operational performance was probably due to the relocation of the inlet-bearing support. These benefits, however, did not change the point of violent surge. Points A and B on the performance curve (fig. 5) represent operating occurrences similar to those at an equivalent tip speed of 1653 feet per second.

The minimum amount of discharge air necessary to be recirculated for a desired increase in net stable-air-flow operating range can be obtained from figure 6. The recirculated air flow is expressed as a percentage of the net impeller-inlet air weight flow. The contour for 0 percent recirculation represents the normal surge line of the compressor unit with the surge inhibitor installed. The broken contour line between the curves at equivalent tip speeds of 1653 and 1738 feet per second represents condition A (fig. 5) and is not a member of the family of curves indicating the amount of air recirculated.

Effect of Surge Inhibitor on Efficiency and Pressure Ratio

The installation of the surge inhibitor on the unit impaired neither the efficiency nor the pressure ratio in the region of normally stable air flow (figs. 5 and 7). The slight improvement in performance characteristics at the lower equivalent tip speeds (fig. 5) can probably be attributed to the relocation of the inlet-bearing support.

One of the principal benefits resulting from the use of the surge inhibitor was the 5-point gain in peak adiabatic efficiency at the equivalent tip speeds of 1653 and 1738 feet per second (fig. 5). The accompanying increase in pressure ratio was 0.63 (fig. 7). The region of higher efficiency and pressure ratio would have been impossible to attain on this particular compressor unit without using the surge inhibitor to pass through the critical flow condition.

With the surge inhibitor in operation in the region of normally unstable air flow, a drop in pressure ratio was obtained as the net volume flow was reduced (fig. 8). This condition was partly a result of the corresponding increase in the temperature and the prerotation of the air at the impeller inlet. Pressure losses at the impeller inlet caused by the mixing of the recirculated and the inlet air caused a further decrease in pressure ratio and a corresponding drop in efficiency.

The pressure losses at the impeller inlet were large for the installation with the surge inhibitor. If the net volume flow were reduced by wasting part of the volume flow at the compressor discharge, the resulting efficiency would be slightly higher than that obtained for the same pressure ratio and volume flow with the reported method of recirculation. The pressure losses at the compressor inlet with the surge-inhibitor installation were therefore greater than the kinetic energy of prerotation of the recirculated air. In spite of these pressure losses, the use of the surge inhibitor permitted a moderate extension of the stable-air-flow operating range without a formidable drop in efficiency. The use of the surge inhibitor permitted the attainment of higher pressure ratios and efficiencies at the high tip speeds, a benefit which could never have been realized by simply wasting part of the air.

Because of the large inlet and outlet volumes of the test rig, the surging characteristics of this compressor were probably poorer than of one installed in an aircraft power plant. (See reference 10.) The losses occasioned by the use of the surge inhibitor as part of an engine assembly may therefore be expected to be no higher than those reported herein.

SUMMARY OF RESULTS

From an investigation of the performance of a compressor unit with a surge inhibitor, the following results were obtained:

1. A considerable gain in stable-air-flow operating range was obtained over a range of equivalent impeller tip speeds of 1255 to 1738 feet per second. The surge inhibitor, although designed to triple the stable-air-flow operating range at an equivalent tip speed of 1550 feet per second, was capable of increasing the net stable-air-flow operating range more than eight times the original value at this tip speed. The efficiency and the pressure ratio of the compressor in the normal unstable-air-flow operating range, however, was less than the peak value of the corresponding equivalent impeller tip speed.

2. The installation of the surge inhibitor on the compressor unit did not impair the efficiency nor the pressure ratio in the normal stable-air-flow operating range.

3. At the equivalent tip speeds of 1653 and 1738 feet per second, the surge inhibitor permitted operation through a critical flow condition into a region of higher efficiency and pressure ratio. An increase of 5 points in peak efficiency and a corresponding increase of 0.63 in pressure ratio was obtained at these tip speeds.

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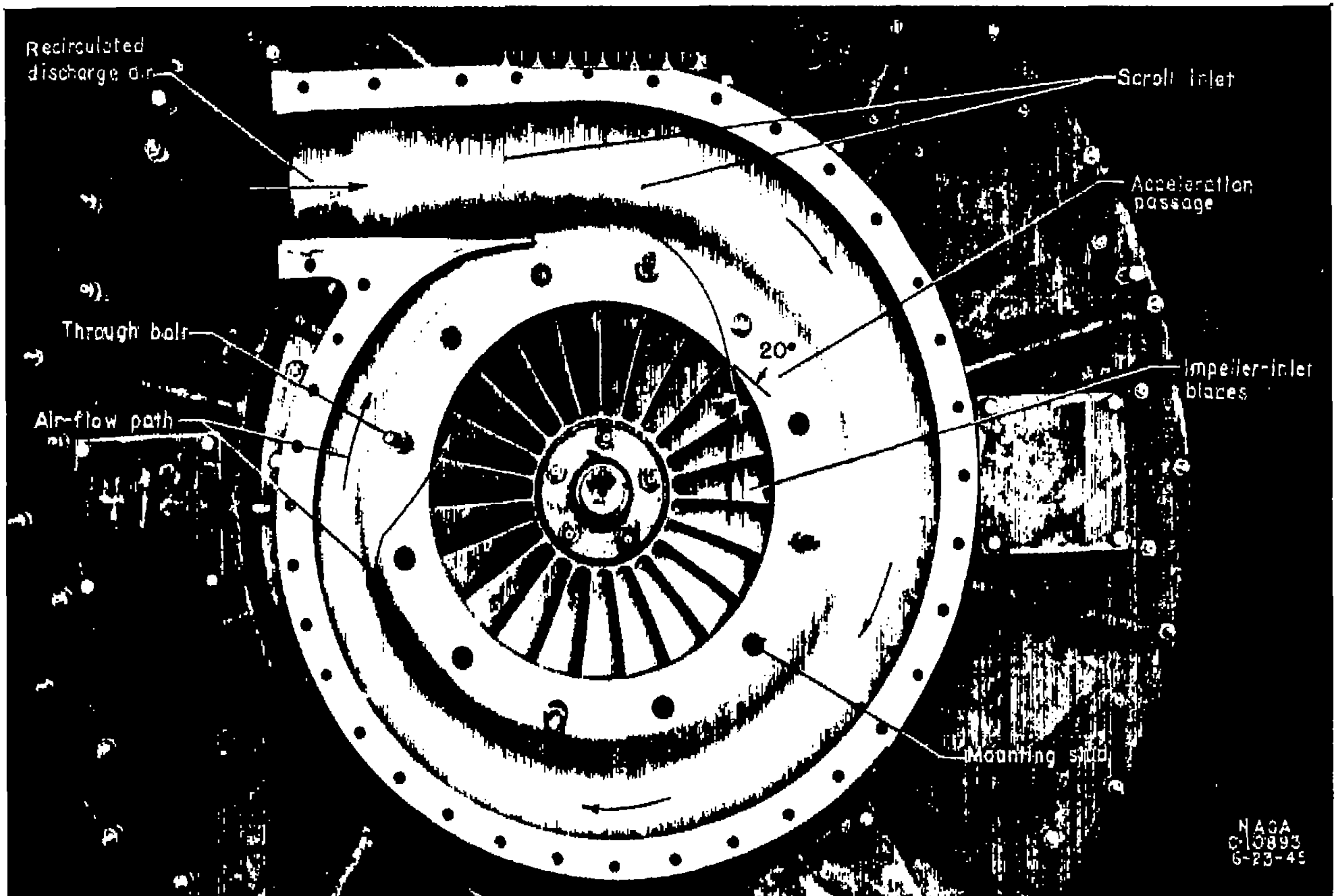
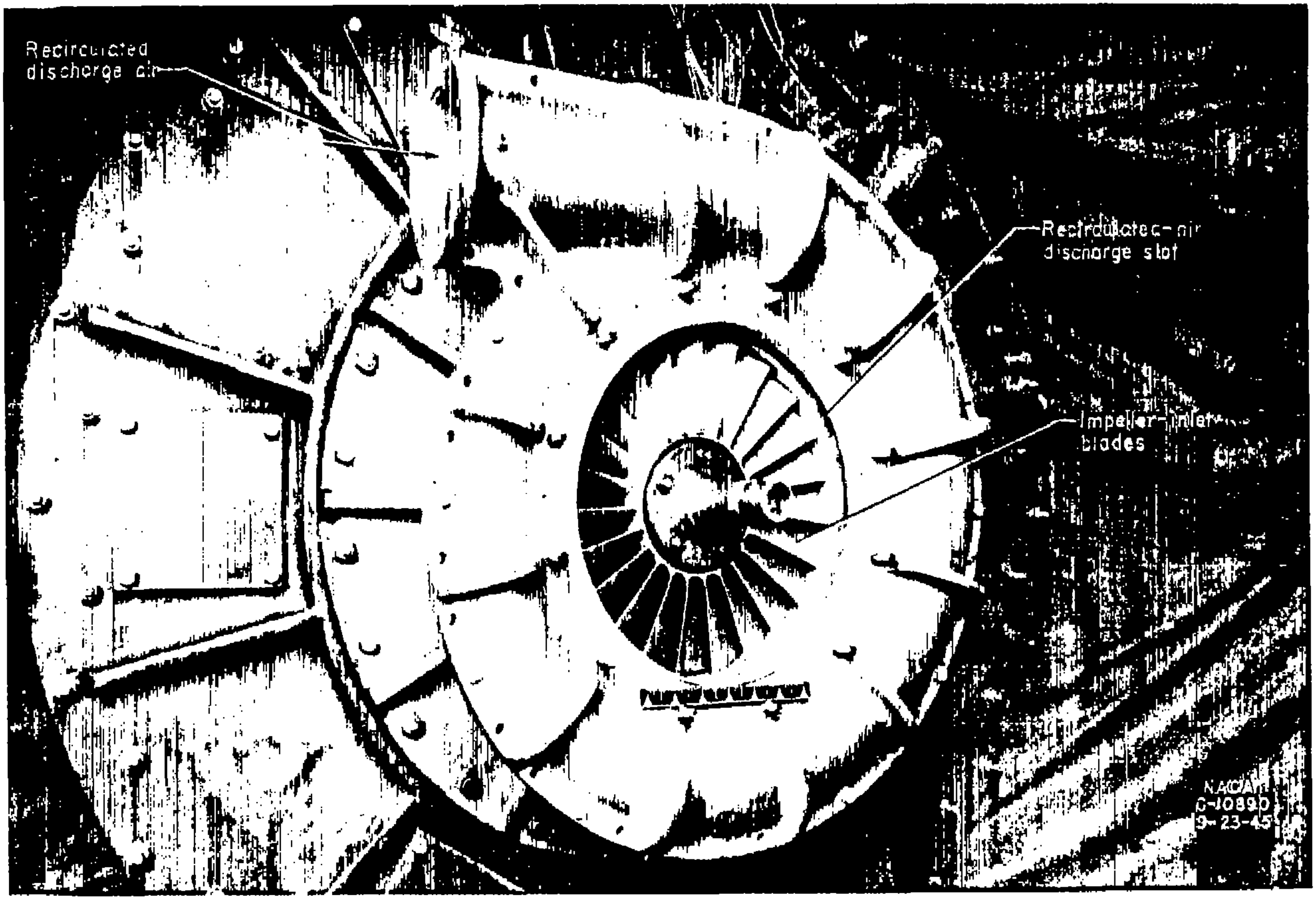


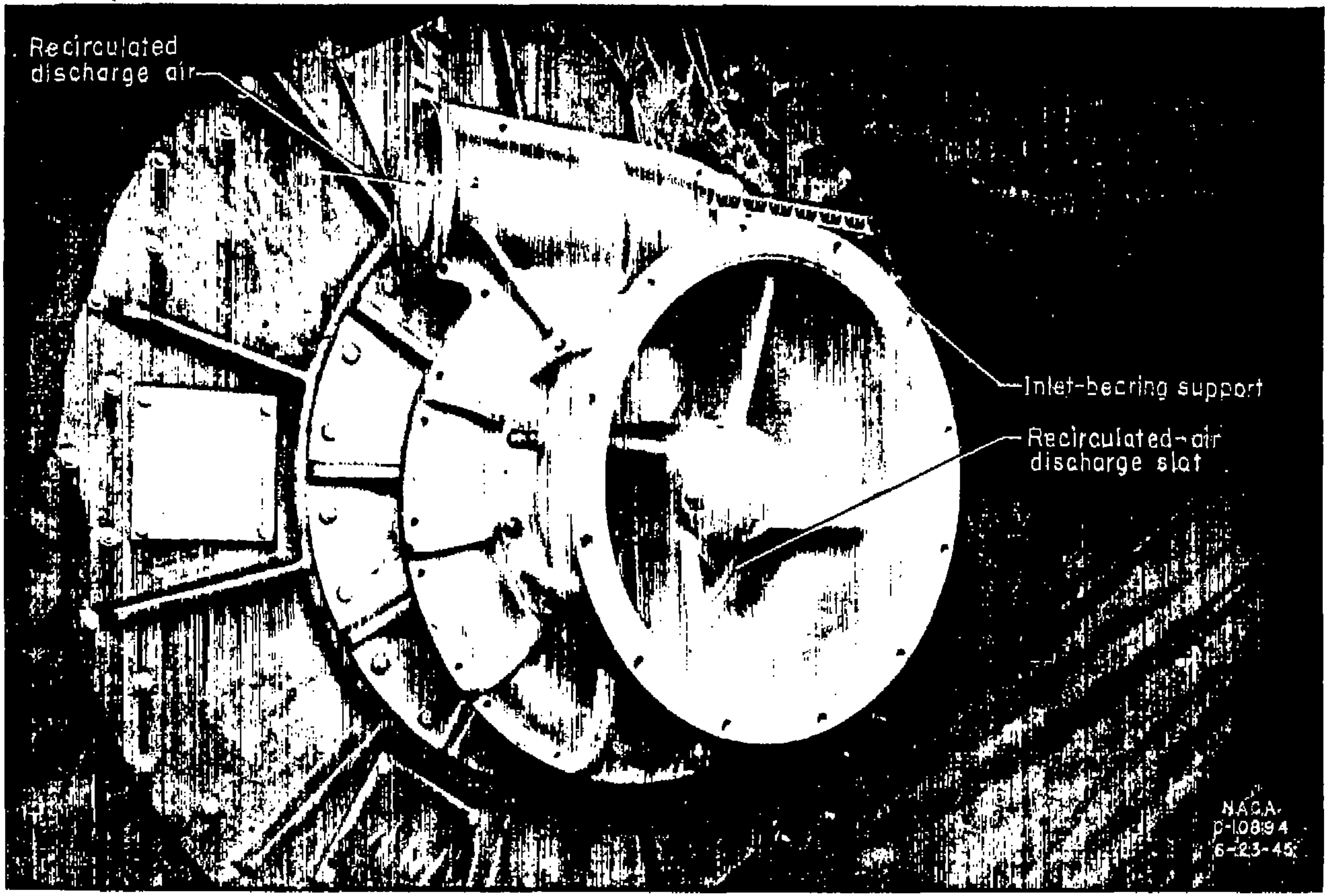
(a) Rear section.

Figure 1. - Surge inhibitor mounted on test rig.



(b) Both sections.

Figure 1. - Continued. Surge inhibitor mounted on test rig.



(c) Assembled with inlet-bearing support.

Figure 1. - Concluded. Surge inhibitor mounted on test rig.

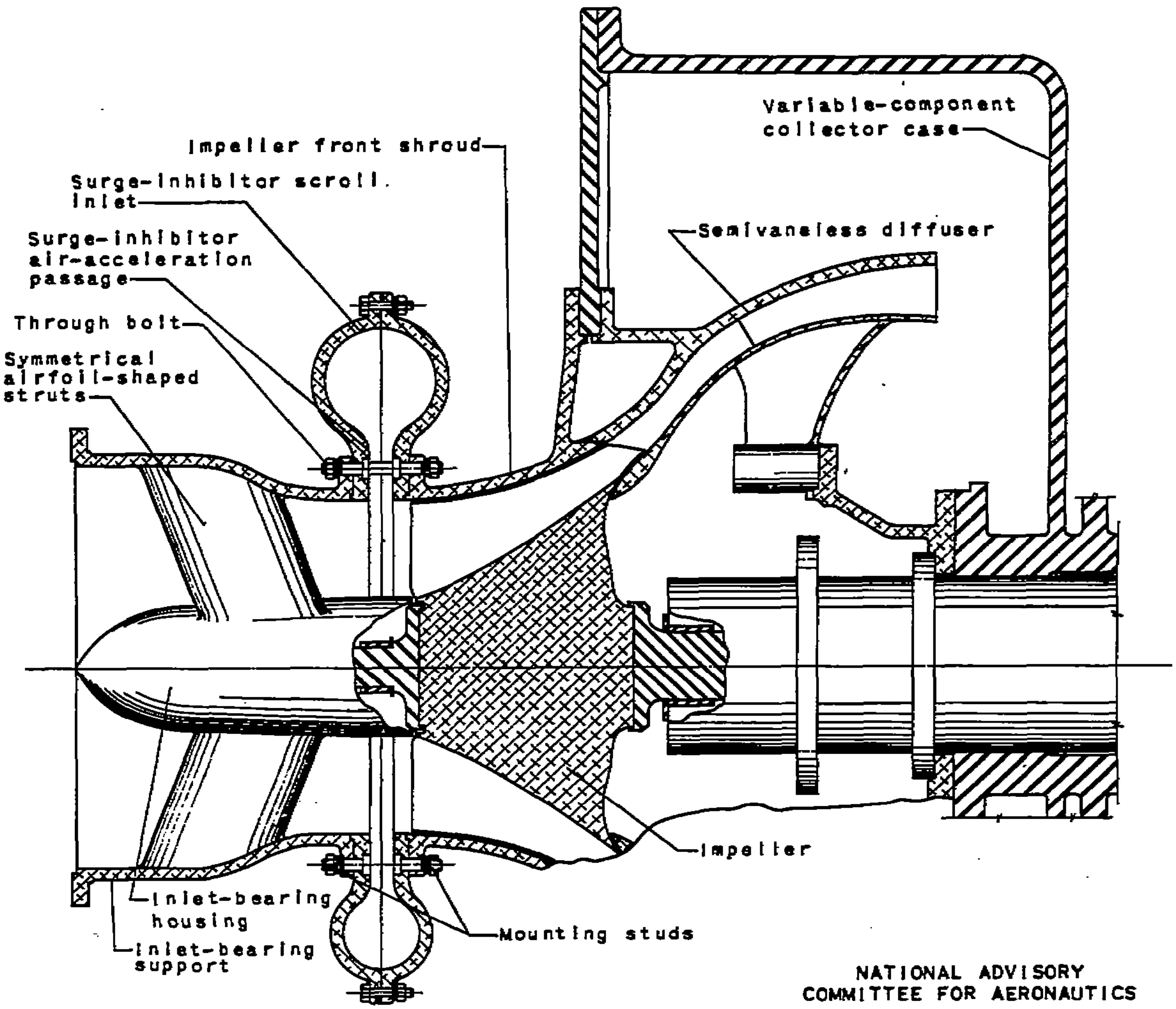


Figure 2. - Cross-sectional drawing of surge inhibitor assembled with compressor unit on variable-component collector case.

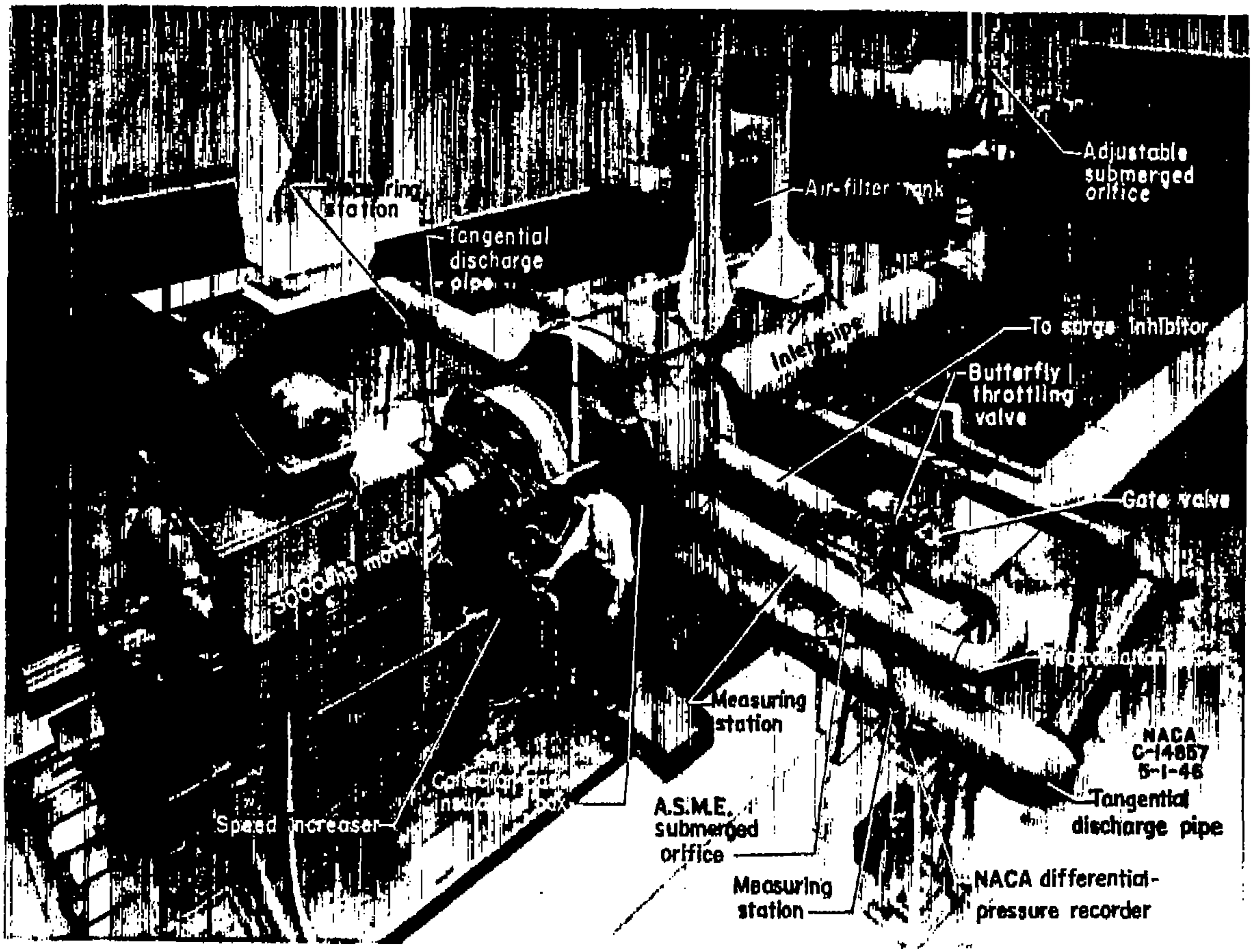


Figure 3. – Test setup for surge-inhibitor tests.

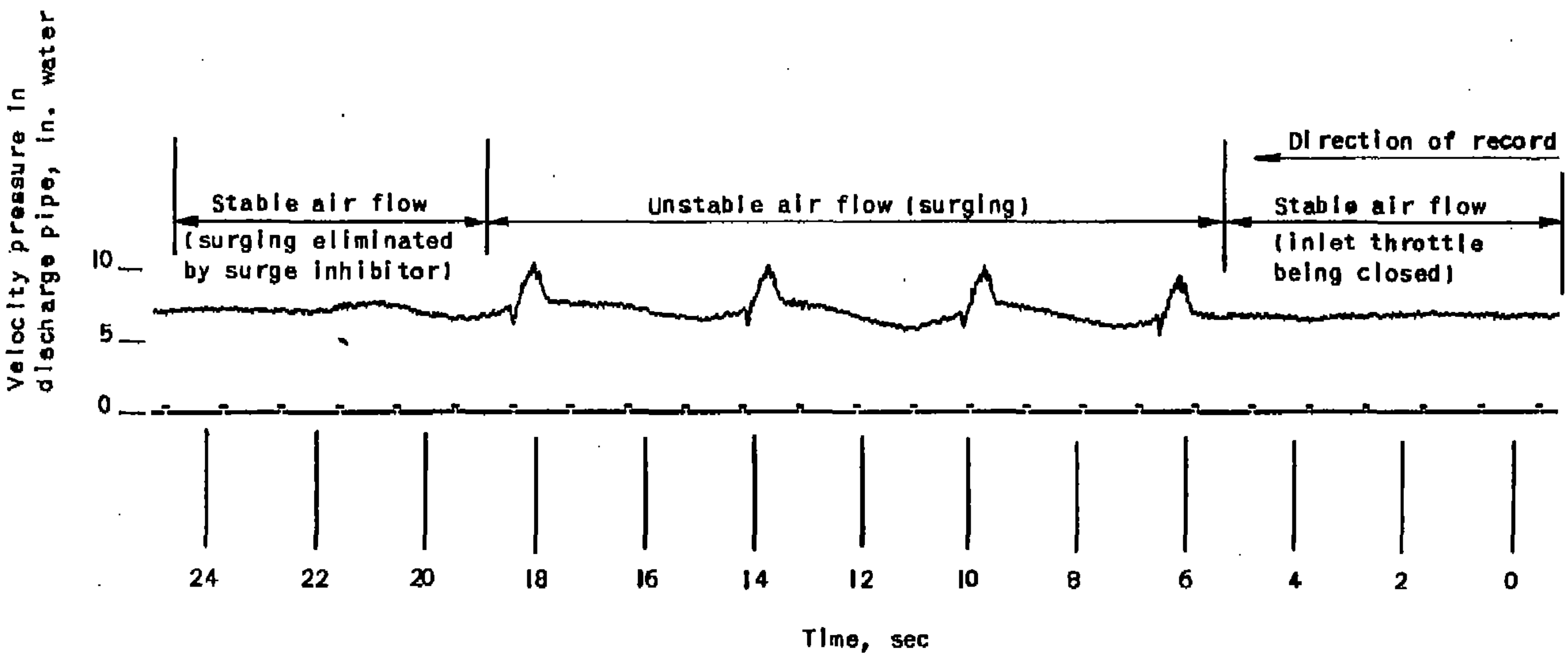


Figure 4. - Typical velocity-pressure trace of stable air flow and surging.

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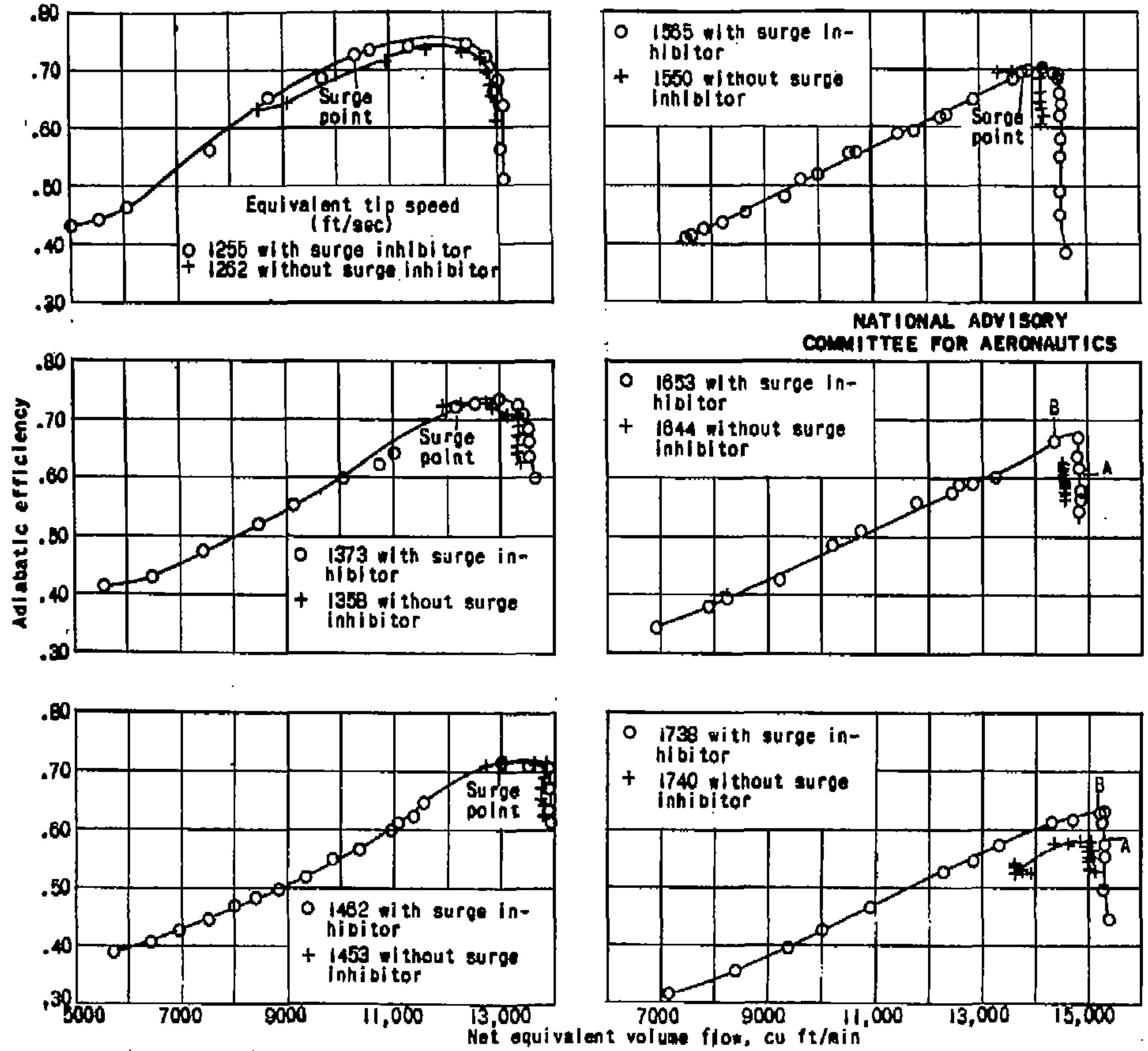

Figure 5. - Comparison of stable-air-flow operating range and adiabatic efficiency at various equivalent impeller tip speeds of the compressor unit with and without surge inhibitor installed. (Data without surge inhibitor from reference 3.)

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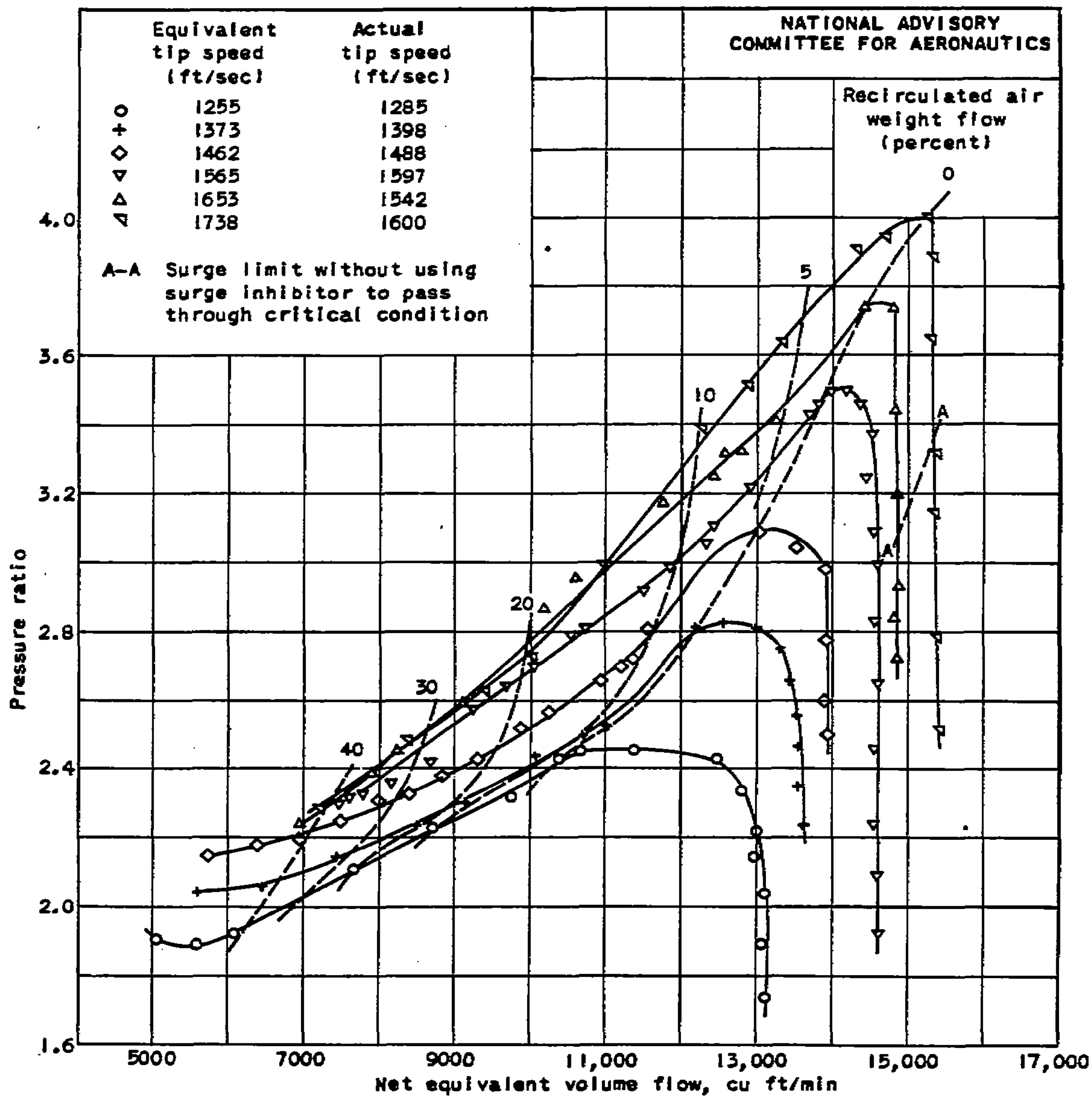

Figure 6. – Percentage of net air weight flow to be recirculated for given increase in net stable-air-flow operating range.

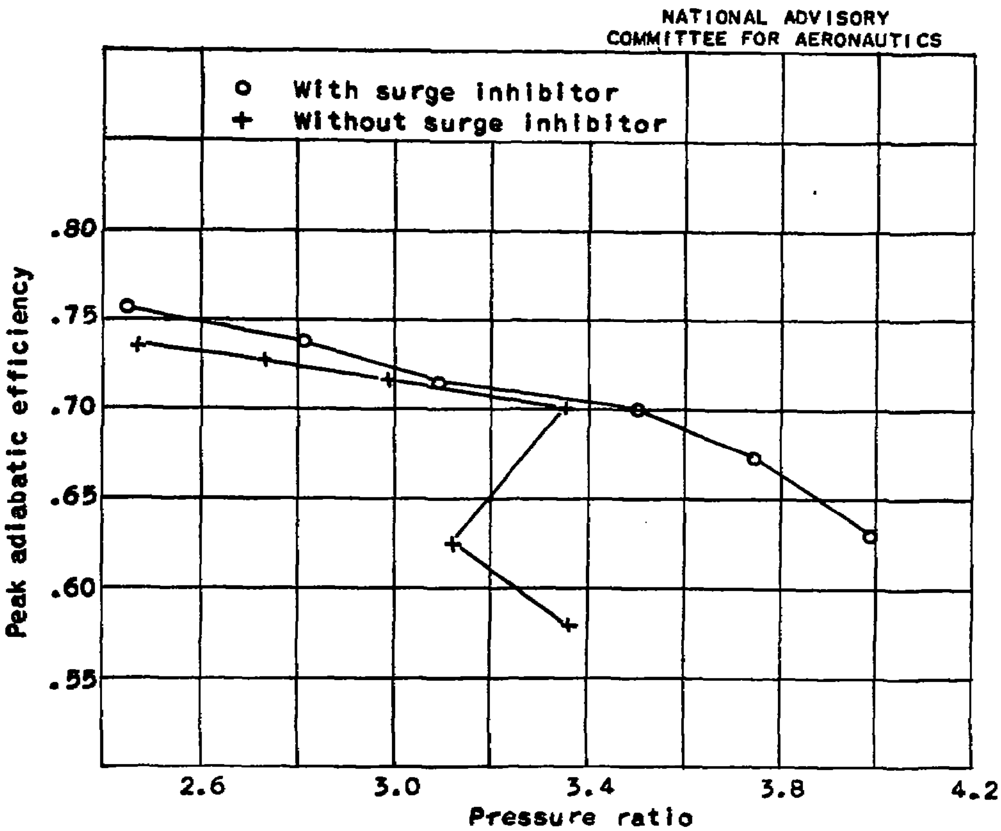

Figure 7. - Comparison of peak adiabatic efficiency and corresponding pressure ratio of compressor unit with and without surge inhibitor installed.

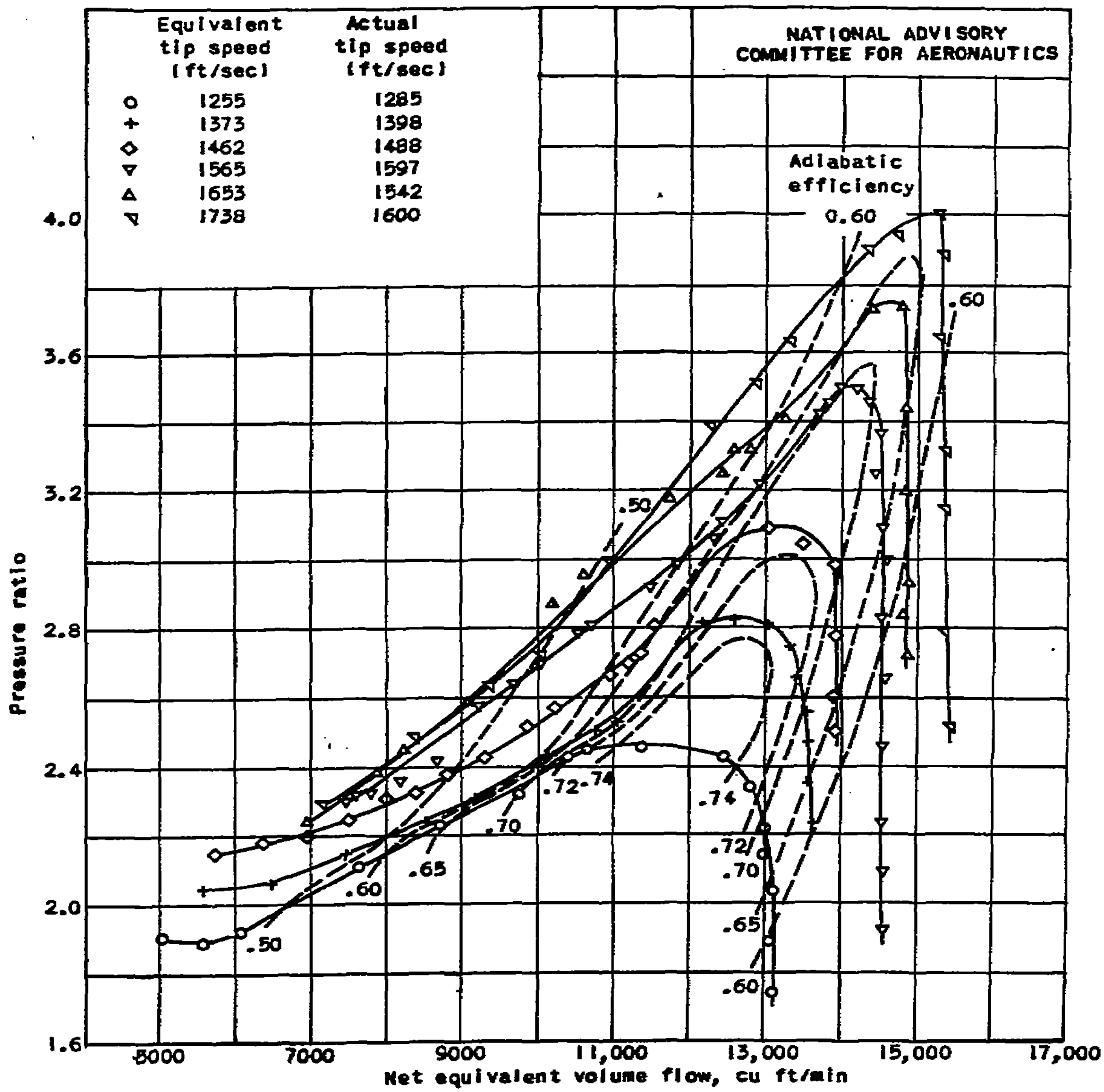

Figure 8. – Performance characteristics of compressor unit with surge inhibitor installed.